HF Radar Measurements of Ocean Surface Currents and Winds

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LONG-TERM GOAL

The long term goal of this research is to develop multifrequency, high frequency (HF) radar techniques and instrumentation for measuring surface currents, waves and winds in coastal regions and large lakes for scientific, civil and military applications. A related goal is to investigate and develop ship detection and tracking techniques for multifrequency HF radar. The goals include deployment of HF radar systems in coastal regions for air-sea interaction, coastal oceanography and ship detection research.

OBJECTIVES

The objectives of this project began with the construction and deployment of two and later three multifrequency HF radar instruments (called MCR for Multifrequency Coastal Radar) to Monterey Bay, California. Further experiment deployments were to the Virginia coast and to Lake Michigan for fresh water experiments (NSF sponsorship). The data collected at these sites is to be reduced, analyzed and interpreted to achieve the specific research objectives listed below:

1. Ocean science investigations, including assimilation of HF radar data into coastal ocean circulation models, and air-sea interaction studies

2. Improvement of radar performance by upgrading hardware and software and developing improved transmit antennas, effective coded waveforms and flexible use of multiple frequencies

3. Improvement of HF radar estimates of surface currents and current shear by developing an improved estimation algorithm that uses physical knowledge of surface layer hydrodynamics

4. Estimate surface wind speed and direction using multifrequency HF radar measurements by exploiting the ability of the radar to measure vertical current shear and air-sea interaction theory

5. Use of continuing HF radar observations on Monterey Bay in observing ships to assess the usefulness of multiple frequency HF radar in ship detection and tracking.

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14. ABSTRACT
The long term goal of this research is to develop multifrequency, high frequency (HF) radar techniques and instrumentation for measuring surface currents, waves and winds in coastal regions and large lakes for scientific, civil and military applications. A related goal is to investigate and develop ship detection and tracking techniques for multifrequency HF radar. The goals include deployment of HF radar systems in coastal regions for air-sea interaction, coastal oceanography and ship detection research.

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APPROACH

This project requires an expert team of engineers and oceanographers from many institutions, including Peter Hansen, Lorelle Meadows and Yolanda Fernandez (University of Michigan), Calvin Teague (Stanford University), Robert Onstott (ERIM International), Dan Fernandez (California State University, Monterey Bay), Jeff Paduan (Naval Postgraduate School) and Kenneth Laws, Michal Plume, Jessica Drake and Steve Petersen (University of California at Santa Cruz). This team designed, constructed, upgraded and deployed MCRs at sites on the Atlantic and Pacific oceans as well as the Great Lakes. We continually seek to deploy MCR systems for air-sea and ship observations in long term observations and short campaigns. The specifics of our approach are summarized as follows:

1. **Ocean science investigations:** participate in assimilation of HF radar data into the coastal ocean circulation model of Igor Shulman (Southern Mississippi); continue investigations of air-sea interaction, including momentum transfer and structure of the air and sea boundary layers.

2. **Improve radar performance** by upgrading radar hardware and software, repairing and upgrading the radar antennas, especially transmit antennas, and comparing MCR with other HF systems.

3. **Improve HF radar estimates of surface currents, current shear and winds** by developing an improved estimation algorithm that uses physical knowledge of surface layer hydrodynamics, e.g. based on the Charnock relation, and continued work on MUSIC and beamforming.

4. **Estimate surface wind vectors using multifrequency HF radar measurements** by using air-sea interaction theory and the ability of MCR to measure vertical current shear.

5. **Use the continuing HF radar observations on Monterey Bay to observe ships** (especially known ships at known locations) at multiple HF frequencies, noting changes in detection and tracking performance with frequency, range, direction, ship type, etc.

WORK COMPLETED

1. **Observational program:** We strive to keep the MCR units in operation either at Monterey Bay, their "home site," or employed in experimental campaigns elsewhere. During the last year three MCRs operated on and near Monterey Bay. This includes monitoring, maintenance and upgrades.

2. **Analysis of COPE-3 experiment data:** In the autumn of 1997 an extensive field experiment was conducted in the Atlantic Ocean off the Virginia coast, near the mouth of Chesapeake Bay. This included a determination of the effective depths of HF radar measurements by Teague et al. (2001).

3. **Simulation of HF radar data processing:** There are two basic methods of data processing for HF radar, namely beamforming and MUSIC. Detailed simulations of the two methods has resulted in a much better understanding of the advantages and disadvantages of each – see Laws et al. (2000).

4. **Comparison of MCR and SeaSonde measurements of surface currents on Monterey Bay, CA:** We compared surface current measurement results of MCR and SeaSonde (CODAR Ocean Systems instrument) systems using data from co-located sites – see Vesecky et al. (2001).

5. **Further analysis of surface currents for a land-sea breeze case:** Monterey Bay provides an ideal location for studying the surface current response to the diurnal variation in surface winds provided by a land-sea breeze. We employed complex correlation and rotary spectra to study the surface wind and surface current relationships in the top 2 m of the ocean – see Vesecky et al. (2001).

6. **Investigation of the performance of HF radar over fresh water** using data collected from the Lake Michigan deployments as well as theoretical calculations – see Fernandez et al. (2000).

7. **Multifrequency observations of ships on Monterey Bay and Lake Michigan** were analyzed and modeled. Results were published by Fernandez et al. (2001).

8. **Estimation of wind friction velocity (u*) using multifrequency HF radar:** Multifrequency HF radar observations of currents at different depths are used with hydrodynamic theory to find u*.

9. **Communication of research results:** This year we presented eight papers at four major conferences and workshops on remote sensing and oceanography, including IGARSS and the Radio Oceanography Workshop, sponsored by ONR. Four refereed journal papers were published.

10. **Ph. D. student graduated:** We are pleased that Kenneth Laws received his Ph. D. in March, 2001 from the University of California at Santa Cruz (see Laws, 2001 below).

RESULTS

This year produced many new results with the analysis of past field observations. Below are two that are particularly important to the field. One concerns the depths to which HF radar observations at different frequencies refer and one shows a comparison of HF observations with model results for near shore currents in Lake Michigan.

Multifrequency HF radar (MCR) measurements refer to increasing depths below the surface as radar wavelength increases. However, estimating the “effective” depths of MCR has been difficult, both in theory and measurement. The work of Stewart and Joy and later Ha shows that using the theory of linear ocean surface waves one expects the effective depth to be about 4% of the radar wavelength under the assumption of a logarithmic profile of surface current with depth and 8%, or a depth of (1/2k), where k is the ocean wavenumber corresponding to 1/2 the radar wavelength, when a linear profile is assumed. However, current profiles very near the surface are very hard to measure and only a few laboratory wave tank experiments exist. So there is significant doubt about the true situation on the real ocean. During COPE-3 MCR observations by Teague et al. (2001) were used to compare HF radar estimates of near-surface currents with a bottom mounted acoustic Doppler current profiler (ADCP). HF and ADCP current estimates were examined in a regression analysis against the 2-m depth ADCP data. In Fig. 1 we show the location of the measurements near the mouth of Chesapeake Bay and a plot of the slope of the regression as a function of depth. The HF radar measurements are plotted using a depth of (1/2k) corresponding to a linear profile of surface current with depth. The regression slope S shows S=1 at depth 2 m as it should since this point is 2-m ADCP data regressed against itself. At depths greater than 2 m the slope decreases showing that current fluctuations at these depths are smaller than at 2-m as one expects. At shallower depths the HF measurements show S >1 indicating larger current fluctuations than at depth = 2 m. This is due to wind stress more strongly influencing the shallower depths. At a depth of about 60 cm (21.8 MHz HF radar measurements) the current fluctuations are ≈ 20% larger than at 2-m, i.e., S ≈ 1.2. We conclude that these measurements are consistent with the (1/2k) depth assignment for HF radar measurements. This information will allow better combining of data from HF radars operating at different frequencies that refer to different depths.

One of the most useful applications of HF radar measurements is assimilation into regional circulation models. During deployment of MCR systems to the shore of Lake Michigan we also have results of the Princeton Ocean Model (POM) adapted to Lake Michigan (kindly provided by Drs. David Schwab and Demetri Beletski of the NOAA Great Lakes Environmental Laboratories). The first step in assimilation is to bring together the circulation model and the relevant environmental measurements. In Fig. 2 we show POM model runs and HF radar data for the same time period in April 2000. The HF radar observations are limited in extent over the fresh water lake by very large propagation losses. Early on April 8 (left panels in Fig. 2) the dominant flow is from north to south along the Lake Michigan shore due to a northerly wind. By 1800 on April 9 a strong impulsive-wind-driven current had moved from north to south along the western shore of the lake, around the bottom and up the eastern shore to the location of the observations. By the 9th the flow around the observation area had reversed as shown in both the model calculations and the HF radar observations. One sees general agreement between model and measurements, but still significant differences. HF and ADCP current measurements can make model calculations more accurate by using a data assimilation process.

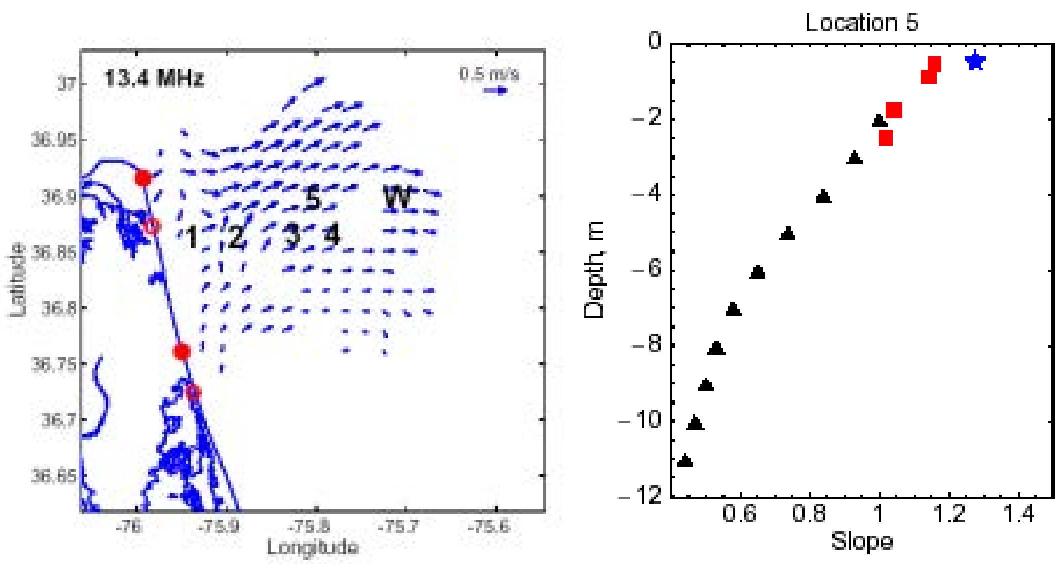

Fig. 1. At left is an MCR surface current map near the mouth of Chesapeake Bay. Note how a northward flow along the coast from the south meets a southward flow out of the Chesapeake Bay mouth (top left), forming an offshore jet. At right is a plot of regression slope as a function of depth of measurement. Triangles are ADCP measurements, squares are MCR measurements (at 4.8, 6.8, 13.4 and 21.8 MHz) plotted at a depth of (1/2k) and the star is a SeaSonde HF radar measurement at 25 MHz. Note how the HF radar measurements continue the trend curve of the ADCP measurements.

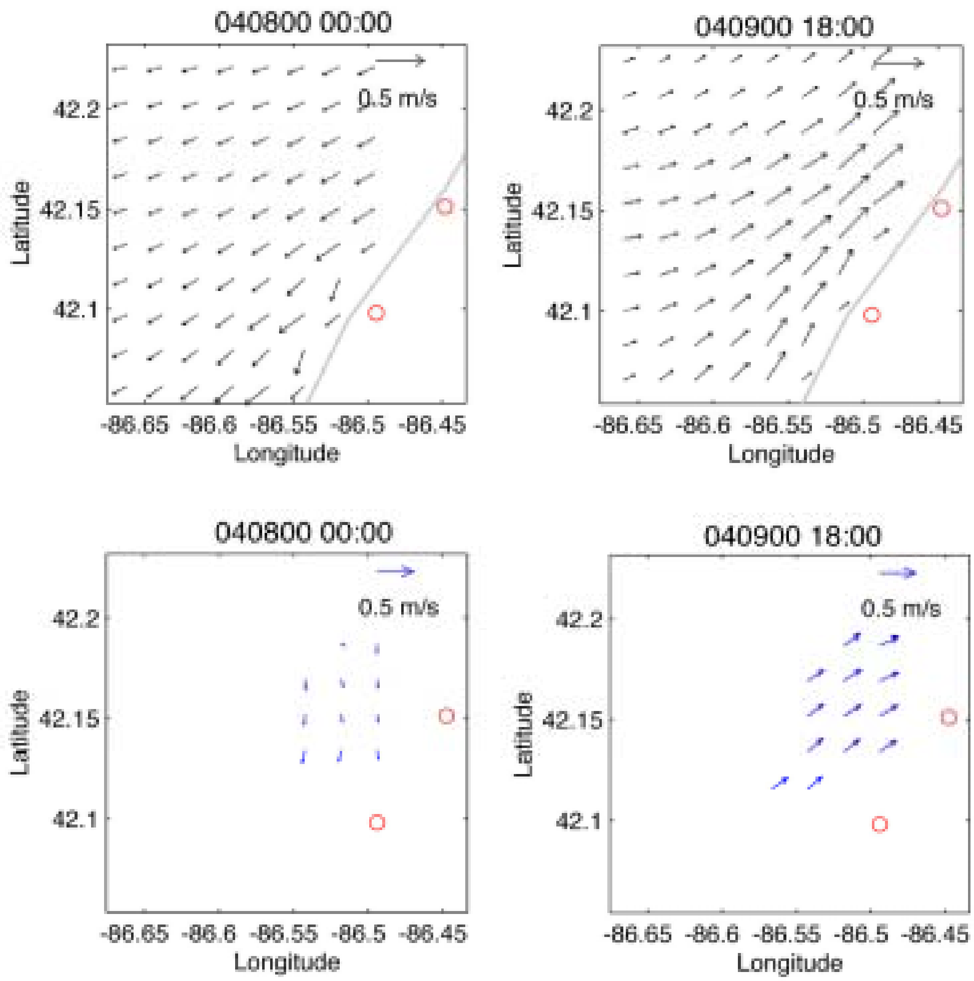

Fig. 2. Surface current flow on a 2 km grid along the eastern shore of Lake Michigan, near St. Joseph, MI. The two red circles are the two HF radar field sites ≈ 6 km apart along the shoreline. In the top row are POM circulation model calculations for early on April 8, 2000 and at 1800 on April 9th after a flow reversal due an episodic wind-driven current event. The 4.8 MHz HF measurements, correspond to a depth of ≈ 2.5 m, are shown on the bottom row.

IMPACT/APPLICATION

Multifrequency HF radars have demonstrated their usefulness in measuring surface currents and current shear in the top few meters of the ocean. No other technique makes such measurements over a large area, at reasonable cost. We have extended multifrequency applications to fresh water. HF radars are especially useful for applications where real time forecasts of coastal surface currents are needed.

RELATED PROJECTS

1. We deployed MCRs on the shore of Lake Michigan during 1998-2000 to help define lake circulation during episodic resuspension events (NSF and NOAA, project EEGLE).

2. We also participated in the Integrated Coastal Ocean Network (ICON) project (National Ocean Partnership Program), integrating in situ and remote measurements over Monterey Bay.

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Vesecky, J. F., Y. Fernandez, K. Davidson, J. D. Paduan, C. C. Teague, J. Drake and M. A. Plume, Air-sea interaction observed by HF radar on Monterey Bay, **IGARSS 2001,** Sydney, Australia, (2001)

Papers presented at the **ONR Radio Oceanography Workshop**, April 2001 at Timberline Lodge OR

- Fernandez, D. M., Statistical errors associated with HF radar measurements by a phased array
- Paduan, J. D., Effect of Stokes drift on HF radar measurements
- Paduan, J. D., Statistics and data assimilation results from long-term HF radar-derived surface currents around Monterey Bay
- Teague, C. C., Status of multi-frequency coastal radar
- Teague, C. C., On the effective depth as a function of radar frequency
- Teague, C. C., Ionospheric effects on HF radar observations
- Vesecky, J. F., Multi-frequency and single-frequency surface current measurement comparison